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1994 December 23

Dr. Herschel S. Pilloff
Chemistry and Physics Division (Code 331)
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5660

Dear Hersch,

This letter constitutes the annual report of work carried out under ONR Grant No. N00014-93-1-0116 (R&T No. 4124112–08) at the University of New Mexico during the period 1993 December 1 to 1993 November 30.

During the reporting period five people were directly associated with my research group at UNM. Rüdiger *Schack* continued as the Center for Advanced Studies Postdoctoral Fellow at UNM, working mainly on topics not directly related to this grant; *Schack* left UNM on November 1 to become a postdoc in Ian Percival's group in London. Shang *Song*, USC graduate student, completed her Ph.D. in Physics in 1994 February, working on topics directly related to this grant; she has now accepted a position with Chase Manhattan Bank. Chris *Fuchs* and Howard *Barnum*, UNM graduate students, continued in my research group, both working on topics associated with this grant. *Fuchs* should finish his Ph.D. thesis during this academic year. Dierk *Steinbach*, graduate student from the University of Ulm, joined my research group in 1994 August.

In addition to the above personnel, several visitors were brought to UNM under the auspices of the Center for Advanced Studies: (i) Gerard Milburn of the University of Queensland visited for a brief period in May (and will return for a four-month sabbatical in the spring of 1995); (ii) Samuel Braunstein of the Weizmann Institute visited for two months beginning in mid-May, working directly with *Barnum*, *Fuchs*, and me on topics supported by this grant; and (iii) Gershon Kurizki of the Weizmann Institute visited for a month beginning in mid-August, interacting with my group on various topics in quantum optics.

Research during the reporting period was concentrated in the following areas:

During the reporting period *Caves* was an invited speaker at the Sixth New Zealand Symposium on Quantum Optics, held in Rotorua, New Zealand, 1994 January 24–28, at the International Conference on Fundamental Problems in Quantum Theory, held in Baltimore, 1994 June 18–22, and at the Fourth Drexel Symposium on Quantum Nonintegrability: Quantum-Classical Correspondence, held in Philadelphia, 1994 September 8–11. Braunstein was an invited speaker at the International Workshop on Quantum Communications and Measurement, held in Nottingham, England, 1994 July 11–16, where he reported on joint work with Caves supported by this grant.

Sincerely,

Carlton M. Caves

CMC/TEX

Publications published

1. C. M. Caves and P. D. Drummond, "Quantum limits on bosonic communication rates," *Reviews of Modern Physics* **66**, 481–537 (1994).
2. S. L. Braunstein and C. M. Caves, "Statistical distance and the geometry of quantum states," *Physical Review Letters* **72**, 3439–3443 (1994).
3. C. A. Fuchs and C. M. Caves, "Ensemble-dependent bounds for accessible information in quantum mechanics," *Physical Review Letters* **73**, 3047–3050 (1994).

Publications submitted

4. S. L. Braunstein and C. M. Caves, "Geometry of quantum states," in *Fundamental Problems in Quantum Theory*, edited by D. Greenberger, *Annals of the New York Academy of Sciences*, to be published.
5. C. A. Fuchs and C. M. Caves, "Bounds for accessible information in quantum mechanics," in *Fundamental Problems in Quantum Theory*, edited by D. Greenberger, *Annals of the New York Academy of Sciences*, to be published.
6. S. L. Braunstein and C. M. Caves, "Geometry of quantum states," in *Quantum Communications and Measurement*, edited by R. Hudson, V. P. Belavkin, and O. Hirota (Plenum, New York, to be published).
7. C. A. Fuchs and C. M. Caves, "Mathematical techniques for quantum communication theory," in *Quantum Communications and Measurement*, edited by R. Hudson, V. P. Belavkin, and O. Hirota (Plenum, New York, to be published).

• *Song* and *Caves* finished their work on quantum limitations on phase measurements made by high-precision interferometry, and ***Song*** submitted the work as her USC Ph.D. thesis.

• Braunstein and *Caves* generalized their work on the geometry of quantum states and its relation to high-precision measurements. Their findings, which place absolute limits on how well quantum measurements can determine a c-number parameter and establish new uncertainty principles for a parameter and its conjugate operator, have been published as publication #2. Elaborations of the original investigation, which emphasize the importance of quantum geometry, have been written up as publications #4 and #6. As evidenced by the following research descriptions, this work of Braunstein and *Caves* has opened up an entirely new research area in precision measurements and communications theory.

• *Fuchs* and *Caves* applied the work of Braunstein and Caves to finding new bounds on how much information can be transmitted down a quantum communication channel and to new estimates of the precision of quantum statistical inference. Three manuscripts describing these investigations (#3, #5, and #7) have been prepared for publication.

• Braunstein, Milburn, and *Caves* applied the work of Braunstein and *Caves* to formulating generalized Mandelstam-Tamm uncertainty relations. Their work leads naturally to a uncertainty relations for time and energy and for phase and photon number and also gives Lorentz-invariant uncertainty relations involving the Lorentz-invariant interval and the boost parameter of special relativity. A manuscript describing this work is nearly finished.

• Braunstein and *Caves* developed the quantum theory for estimating two parameters and applied it to simultaneous estimation of position and momentum displacements. They were able to give a general proof—free from the linear-coupling assumptions in the original derivation of Arthurs and Kelly—that simultaneous measurements of position and momentum inevitably are contaminated by additional noise that makes them twice as noisy as the naïve uncertainty relation requires. Braunstein has prepared a draft of a paper describing this work.

• *Barnum*, Braunstein, ***Fuchs***, and ***Caves*** began a systematic investigation of quantum geometry and its implications for high-precision measurements, with the aim of assembling in a single paper the important concepts and results.